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Chemigation for Crop Production Management

Many growers are using irrigation systems to apply agricultural chemicals with the water. The method, called chemigation, initially included only materials such as plant nutrients that generally required incorporation into the soil for effectiveness. Chemigation technology is expanding, however, owing to advances in irrigation system design, improved chemical injection equipment, and widespread development and use of agricultural chemicals. Chemicals being applied by this technique include fertilizers, herbicides, insecticides, fungicides, nematicides, growth regulators, and biorationals. The use of chemigation has increased rapidly during the last few years, and an estimated 5.2 million ha in the United States were chemigated during 1985 (15).

Chemigation systems comprise several components: an irrigation pumping station, a chemical injection pump, a reservoir for the chemical, calibration devices, a backflow prevention system, and related safety equipment (Fig. 1). The chemigation components of an irrigation system have been reviewed elsewhere (14) and will not be discussed here.

Fertigation

Chemigation helps ensure that a crop has sufficient nutrients to produce the desired level of growth during all stages of development. Information about the crop can be integrated with nutrient requirements, soil types, and weather variables to optimize yields.

The concept of applying fertilizer with the irrigation water, especially to corn, was introduced over 25 years ago (4). Expansion in irrigated acreage and advances in equipment technology stimulated research efforts to evaluate the effect of fertilizer applied with the irrigation water on corn production and provided principles and practices for expanding this approach to applying chemicals.

The majority of studies on fertigation have focused on efficient management of nitrogen. There is general agreement that research has not yet determined what portion of the total amount of nitrogen should be applied with the irrigation water for corn production on irrigated sandy soils. Scientists in Nebraska, taking into consideration the variety of economic and weather factors, currently suggest that approximately one-third of the total nitrogen requirement be applied with the irrigation water (18). This practice, coupled with the use of nitrogen in a 10-34-0 starter fertilizer solution applied either as a preplant or a sidedress, appears to provide a satisfactory management system for nitrogen on irrigated sandy soils (G. J. Gascho, *personal communication*).

Environmental concerns relate to the use of nitrogen, especially on irrigated corn in sandy soils. It is doubtful if much NO_3-N is leached below the root zone on sandy soils during the growing season in a typical year, but rainfall from early fall through early spring does move NO_3-N below the root zone (8). Because stopping or slowing leaching in sandy soils during the fall, winter, and early spring is not feasible, NO_3-N must be managed during the growing season to prevent movement from the root zone to the groundwater. The potential for such movement can be reduced by adjusting the application rates of nitrogen to the yield goal with irrigation so that carryover nitrogen at the close of the growing season is kept to a minimum.

Sulfur is essential for a fertilizer program for irrigated corn on most sandy soils. The sulfate ion $(SO_4)^{=}$ is mobile, and, therefore, application of this

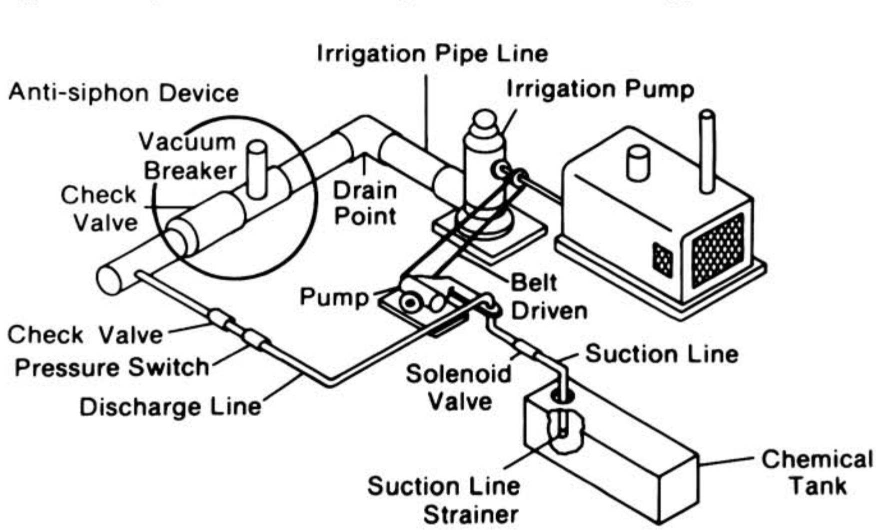

Fig. 1. Chemigation components of an irrigation system.

nutrient with the irrigation water might be justified.

Researchers in the southeastern Coastal Plain have indicated that fertigation via center-pivot irrigation systems can both increase efficiency and lower application costs (11,16,18). Efficiency is achieved because:

1. Nutrients can be applied any time during the plant growth cycle on the basis of need. This is particularly important for the mobile nutrients nitrogen, potassium, magnesium, sulfur, and boron in corn grown in sandy soils.

2. Nutrients can be moved rapidly into the rhizosphere by regulating the amount of water applied and thus be made available for rapid uptake.

3. Nutrients can be applied uniformly over the field. Recent research in Georgia indicated that clear liquids and suspensions are good sources for fertigation. Regardless of the liquid fertilizer formulation applied, distribution was uniform in the irrigation water (C.V. 92–98%) (G. J. Gascho, *unpublished*).

Herbigation

The control of weeds in crops by herbigation is a recent development that increases crop production efficiency by reducing the costs of application, labor, and fuel. Traditional equipment and methods for weed control research are not generally applicable to herbigation, so the principles and concepts governing the behavior of herbicides applied by this method are not completely defined (6,7).

Many herbicides will control weeds selectively in crops (Fig. 2) when applied through a well-designed irrigation system. Herbicides from many classes have been applied by this technology in recent years. These include the preemergence agents alachlor, atrazine, benefin, bensulide, butylate, CDEC, chloramben, cyanazine, cycloate, DCPA, dimethazone, diphenamid, DPX-F6025, EPTC, ethalfluralin, fluometuron, imazaquin, metolachlor, metribuzin, metribuzin + DPX-F6025, oryzalin, pendimethalin, trifluralin, and vernolate. Postemergence herbicides applied through sprinkler irrigation systems include acifluorfen, bromoxynil, chloramben, fluazifop, fomesafen, haloxyfop, lactofen, naptalam + dinoseb, RH-0265, RH-8817, tridiphane, and xylafop; bentazon, glyphosate, imazaquin, MSMA, paraquat, and sethoxydim have also been used but have shown poor or variable activity.

Since 1978, research on herbigation has been conducted with numerous center-pivot systems and with an experimental irrigation system simulator (6,17). Experiments were conducted on soils typical of the southeastern Coastal Plain (sand, loamy sand, or sandy clay loam soils with organic matter content ranging from 0.6 to 2.2% and sand content, from 55 to 94%). Water rates have ranged from 2,715 to 13,576 gal/acre (25.4–127 kl/ha). Research has shown that herbicides can be precisely incorporated to specific depths in the soil depending on the water rate and also provide moisture for activation, crop germination, and growth. Applications after the crop was planted but before crop and weeds emerged provided weed control equal to or greater than that obtained by conventional applications. Crop tolerance to preemergence herbigation has been good to excellent. In many instances, crop tolerance to specific herbicides was better with herbigation than with standard ground application.

The concept of applying postemergence herbigation is even more on the leading edge of pesticide application technology. Under conventional ground or aerial application, postemergence herbicides are normally applied as directed sprays in 1–20 gal/acre (9–187 L/ha). Approximately 100 gal/acre (900 L/ha) of spray solution applied by a ground sprayer will cause runoff from plant foliage, thus reducing the activity of the herbicide. At the present time, it is not feasible to apply postemergence herbicides through sprinkler irrigation in less than 0.1 in. (0.25 cm) or 2,715 gal/acre (25.4 kl/ha) of water, which exceeds the volume necessary to cause foliage runoff by 28 times.

Research on postemergence application of herbicides to crops and weeds has been encouraging, but some results have been variable. With the exception of sethoxydim, all herbicides that showed poor postemergence activity were water-soluble or water-miscible formulations. Addition of a nonemulsified vegetable or petroleum-based oil generally helped to improve or provided more consistent herbicidal activity; the oil carrier did not influence the activity of tridiphane, however.

Increasing the amount of water tends to reduce herbicidal effectiveness, but the encouraging results obtained to date indicate that with more basic research on herbicide absorption and with development of oil formulations, irrigation technology can become a viable option for applying postemergence herbicides. New herbicide chemistry is being developed specifically for postemergence application to crops and weeds, and expanding irrigation research, management, and technology for herbicide application would be desirable.

Insectigation

In the mid-1970s, insecticides were first applied by chemigation to control corn insects, with varying but promising results (17). The first trial was conducted with methomyl, a water-soluble compound, to control the fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (16). Methomyl was injected into a solid-set irrigation system applying various volumes of water. Insect control was inadequate with all volumes of water, and more effective control was necessary for chemigation to be a viable application method. Studies on water-insoluble oil formulations of chlorpyrifos were conducted, therefore, and insect control was markedly improved. These studies confirmed that chemigation of insecticides formulated in oil was an effective method of application.

Following the excellent results with these oil-formulated insecticides on corn, a series of studies was initiated to determine if insects could be controlled on other crops (Fig. 3). Table 1 lists the crops treated by insectigation and the insects controlled with the oil formulations. Some compounds, including dimethoate (Cygon 4WM), methomyl (Lannate, Nudrin 1.8WM), and monocrotophos (Azodrin 5WM), were unsuccessful. The successful compounds, used either as oil additives or as technical plus oil formulations, included acephate (Orthene 75S); carbaryl (Sevin 4-Oil 80S); carbofuran (Furadan 4F); chlorpyrifos (Lorsban 4E) technical; cypermethrin (Ammo, Cymbush 2.0EC, 4-oil 3EC) technical; diazinon 4E; dicofol (Kelthane 1.6EC); disulfoton (Disyston 8E); endosulfan (Thiodan 2E); fenvalerate (Pydrin 2.4EC) technical; malathion 4E technical; methiocarb (Mesurol 75WP); methyl parathion 4EC technical; permethrin (Ambush, Pounce 3.2EC, 2EC) technical; propargite (Comite 6EC); stirofos (Gardona 4F); sulprofos

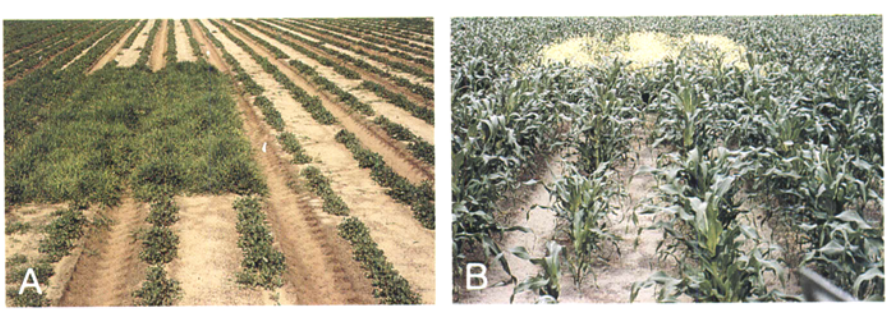

Fig. 2. (A) Metolachlor (1.68 kg a.i./ha) applied in 0.76 cm of irrigation water to control crabgrass, yellow nutsedge, and carpetweed in peanuts; untreated area, left center. (B) Butylate (6.7 kg a.i./ha) + atrazine (1.7 kg a.i./ha) applied preemergence in 0.89 cm of irrigation water to control yellow nutsedge, Texas panicum, morningglory, pigweed, and wild radish in corn; untreated area, top center.

(Bolstar 6EC); thiodicarb (Larvin 4F) oil; and toxaphene 8EC technical. Only carbaryl and chlorpyrifos are currently registered by the Environmental Protection Agency for use in irrigation water.

Fungigation

Fungicides have been applied through overhead sprinkler irrigation systems for more than 10 years (10). Foliar diseases that have been controlled successfully include early blight, late blight, and Botrytis vine rot of Irish potato; Cercospora leaf spot and Rhizoctonia crown rot of sugar beet; early blight, bacterial spot, and Septoria leaf spot of tomato; early and late leaf spots of peanut; and white mold (*Sclerotinia sclerotiorum*) of dry beans (16,18).

Table 1. Crops treated and insects controlled by insectigation

Crop	Insects controlled
Broccoli, cabbage, cauliflower, collards	Cabbage looper, imported cabbage worm
Corn, field and sweet	Corn earworm, fall armyworm, stink bugs, spider mites, aphids
Cotton	Boll weevil, caterpillar group
Cucumbers, squash	Spotted cucumber beetle, pickleworm
Lima beans	Stink bugs, corn earworm
Peanuts	Thrips, leafhoppers, corn earworm, fall armyworm
Snap beans	Thrips
Sorghum	Corn earworm, fall armyworm, stink bugs
Southern peas	Pea weevil, lesser cornstalk borer
Soybeans	Corn earworm, soybean looper, velvetbean caterpillar, stink bugs
Spinach	Vegetable weevil, leafminer, tarnished plant bug
Tobacco	Caterpillars, aphids
Tomatoes	Tomato fruitworm, corn earworm, Colorado potato beetle
Turnips	Diamondback moth, aphids

Applications of fungicides through irrigation water to control foliar diseases of cucumber were as effective as applications with tractor-mounted sprayers when disease-tolerant cultivars were used and epidemics did not develop until near the end of the harvest period (Fig. 4). Epidemics of downy mildew and target spot were not controlled by fungicides applied through irrigation water 8–10 weeks after planting in fall crops. No studies have been conducted with water-insoluble formulations of fungicides for foliar disease control, however.

Several diseases caused by soilborne pathogens have been controlled with metam-sodium applied through overhead irrigation water, e.g., Verticillium wilt (*V. dahliae*) of Irish potato (3); Pythium and Rhizoctonia root rot of collard, spinach, and cucumber; pod rot and Verticillium wilt of peanut; white rot (*Sclerotium cepivorum*) of onion (1); and lettuce drop (*Sclerotinia minor*) (2). Metam-sodium does not control diseases caused by *Fusarium* spp. Other broad-spectrum biocides, such as methyl bromide and DD-MENCS (20% methyl isothiocyanate + 80% chlorinated C_3

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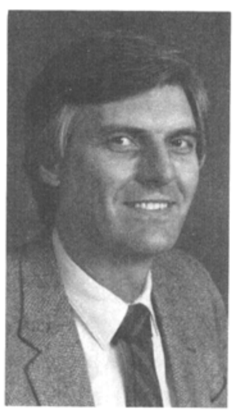

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hydrocarbons), have not been applied through sprinkler irrigation water. PCNB and carboxin applied through irrigation water have provided good control of southern stem rot (*Sclerotium rolfsii*) of peanut in Alabama (18).

Many soil fungicides could be applied through irrigation water if treatment on a broadcast basis was necessary. Soil fungicides are normally applied in-furrow or banded over the row, however. To obtain equivalent concentrations in soil, three to six times as much chemical would need to be applied through irrigation water. Thus, applying soil fungicides through irrigation water to crops in rows 3 ft or more apart may not be economically or environmentally sound. If rows are close or if the entire soil surface is to be treated, however, fungicides may be distributed more uniformly and be more effective against the target pathogens when applied through irrigation water.

For uniformity, application of a fungicide through a moving irrigation system must be continuous. When chlorothalonil was injected continuously through the irrigation line, only 10% was retained on the foliage (18). However, chemigation wets the total leaf surface, especially the lower, more thoroughly than do ground sprays. With solid-set irrigation systems, all of the chemical can be injected in a short time at some point during the irrigation period. Thus, applying a foliar fungicide through the system just before irrigation is completed might be possible.

Nemagation

Historically, nematicides have been one of the most important and reliable means of managing a wide variety of nematodes. By 1965, suitable methods had been devised for applying about 20 nematicides and soil fumigants. The current cost of these methods ranges from $1.94 to $10.23/acre ($4.79 to $25.28/ha), and research has been conducted to develop more economical and efficient application methods.

The first study on nemagation was conducted with three nonvolatile nematicides—carbofuran, ethoprop, and fenamiphos—to control root-knot nematodes (*Meloidogyne incognita* race 1) on direct-seeded tomato for transplant production (9). The nematicides were applied at 10 lb a.i./acre (11.2 kg a.i./ha) through an irrigation riser equipped with an eductor, needle valve, and siphon hose. Ethoprop was phytotoxic, but fenamiphos and carbofuran were not. All reduced the number of root galls, compared with untreated controls, but none controlled *M. incognita* completely. Results encouraged further study, however.

Since 1978, a small-plot irrigation simulator, a solid-set irrigation system, and a center-pivot irrigation system have been used to compare nemagation with conventional application methods. No differences in efficacy of fenamiphos or crop response have been observed (11,16,18). Fenamiphos has been applied via nemagation to many vegetable and agronomic crops, and yields have been increased 3–1,170% over those in untreated plots infested with nematodes (Fig. 5).

The principal use of nematicides is to decrease nematode populations in soil before planting annual crops. The timing and the amount of water, therefore, need to be determined. Fenamiphos (6 lb a.i./acre or 6.7 kg a.i./ha) was nemagated in 0.1, 0.25, 0.50, and 0.75 acre-inch of water (25.4, 63.5, 126.9, and 190.5 kl/ha) on squash at planting and 2 weeks after planting and on corn at planting and 1 week after planting to manage *M. incognita* (18). The soil moisture was at or near field capacity at the time of nemagation. No additional benefits resulted when fenamiphos was applied in volumes of water greater than 0.1 acre-inch (25.4 kl/ha). The low root-gall indices and high yields of squash and corn indicated fenamiphos was more effective when applied at planting rather than after. This new method of application suggests that nematicides could be used as a salvage alternative when nematodes are detected in crops soon after planting.

Nemagation has been used to manage the Columbia (*M. chitwoodi*) and northern (*M. hapla*) root-knot nematodes (12) and *V. dahliae* on potato (11). Ring nematodes (*Criconemella xenoplax*) and *M. hapla* were managed by nemagating oxamyl onto Concord grapes. Nematodes were suppressed and yields increased the second year after application (18).

Cochemigation

Cochemigation increases the economic benefits of irrigation as a management tool in crop production. Limited research has been conducted on the application of herbicides with fluid fertilizers. Tridiphane + atrazine had equal activity when applied in water, in suspension fertilizer, and in nonemulsified oil carrier. Results from other studies have been encouraging with both preemergence and postemergence herbicides. Compatibility problems were not observed when preemergence herbicides were applied with fluid fertilizers in irrigation. Some reduction in herbicide activity was noted, however, when postemergence herbicides were mixed and applied with fluid fertilizers, but this can be corrected with proper timing and herbicide formulation adjustments.

The compatibility and efficacy of the nematicide fenamiphos and the herbicide EPTC were determined when applied together or alone in irrigation water to manage nematodes and weeds on snap bean. The methods were equally effective in crop response, yield increase, and nematode and weed management.

In a recent study (5), fenamiphos and metalaxyl were applied alone or together and incorporated into the soil with a tractor-powered sprayer-Rototiller (conventional method) or applied via chemigation to manage the root-knot/black shank complex on flue-cured tobacco (5). The complex was best managed by applying the chemicals together. Efficacy of fenamiphos or metalaxyl and crop response were not influenced by method of application.

Growth Regulators

The increasing use of center-pivot irrigation systems has led to questions concerning the application of plant growth regulators with irrigation water to control suckers on tobacco. If both contact (fatty alcohols) and systemic (maleic hydrazide) agents for sucker control could be applied successfully with irrigation water and provide the level of control experienced with conventional application, savings in time, equipment, and fuel could result.

When applied via irrigation, contact growth regulators in the current formulation did not provide acceptable control of suckers, but maleic hydrazide provided excellent control. Application of systemic growth regulators via irrigation may offer other advantages, e.g., lower rates and reduced residues, but additional research is needed to demonstrate such benefits.

Fig. 3. (A) Fenvalerate (0.11 kg a.i./ha) applied in 0.25 cm of irrigation water to control cabbage looper on cabbage. (B) Pyrethroid insecticide applied with irrigation simulator to control insects on cotton.

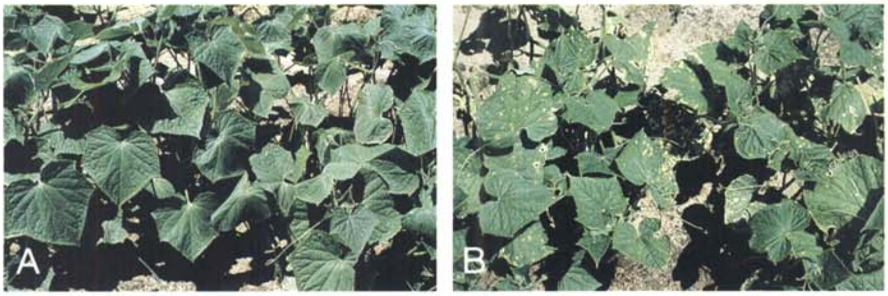

Fig. 4. Cucumber (A) treated with chlorothalonil applied through irrigation water to control foliar diseases and (B) untreated, with anthracnose.

Fig. 5. Squash (A) treated with fenamiphos (8.9 kg a.i./ha) applied in 0.25 cm of irrigation water to control *Meloidogyne incognita* and (B) untreated.

Biorationals

Chemigation is an effective method for disseminating biorationals, i.e., parasites and pathogens of insects and weeds. Preliminary data indicate that application of a baculovirus of the corn earworm and fall armyworm in 2.54–13.2 mm of irrigation water can initiate an epizootic. Larvae of the parasitic Tachinidae fly have been applied to field corn to initiate parasitization of the fall armyworm. Oil formulations of urediospores of rust of yellow nutsedge applied in 2.54 mm of irrigation water initiated pustulation within 7 days and reduced the stand of nutsedge by 70%.

Advantages of Chemigation

Uniform application. Chemicals can be applied more uniformly by a properly designed and maintained sprinkler irrigation system such as center-pivot and linear-move units than by aircraft or ground-based sprayers.

Prescription application. Center-pivot systems can usually be operated in any kind of weather and at any time of day. Chemicals can be applied when needed, instead of when the weather clears or an aircraft pilot can schedule spraying.

Incorporation and activation. With chemigation, fertilizers, herbicides, nematicides, and any other material requiring incorporation and water for activation can be applied to the desired depth and activated immediately. This is far superior to anything possible with a tractor or an aircraft.

Reduction of soil compaction. Driving tractors through the field is avoided with chemigation, thus reducing soil compaction and also the need for energy-consuming and costly deep tillage.

Reduction of mechanical damage to the crop. Operating tractors and high-clearance sprayers to apply chemicals can cause substantial mechanical damage to some crops, e.g., corn, tobacco, and cotton, and increase the incidence of plant diseases in others, e.g., peanuts and vegetables.

Reduction of hazards to the operator. Drift and operator hazard would appear to be increased with chemigation of an insecticide in a large volume (25–190 kl/ha) of water (17). Table 2 shows, however, that the amount of insecticide available per unit volume of spray solution differs greatly according to method of application. The amount of insecticide concentrated in water is 140–1,000 times greater with aerial application and 27–200 times greater with ground-sprayer application than with chemigation. Therefore, worker contact with insecticide in drift, wet foliage, and wet soil during application would be with a more concentrated form in aerial and ground-sprayer applications than in chemigation. Also, chemigation does not require the operator to be in the field, directly exposed to chemical solutions and subsequent drift. Thus, the potential for inhalation or absorption of toxic material is greatly reduced.

Quantitative studies are needed to compare the risks associated with the dilute solutions of insecticides used in chemigation with those in aerial and ground-sprayer applications. However, the degree of dilution incorporated with a "closed system" of application such as chemigation should minimize many of the hazards currently associated with applications of insecticides. For example, the acute dermal LD_{50} of parathion for rats is 55 mg/kg and the acute oral LD_{50} is 4–13 mg/kg. Assuming that toxicity for human beings approximates that for rats, the dermal LD_{50} for a 68-kg person would be 3,745 mg and the oral LD_{50} would be 272–885 mg (Table 3). Dermal LD_{50} would require exposure to the contents of 352 ml of water from aerial application, 1,753 ml from ground-sprayer application, and 190 L from the 25-kl chemigation. Oral LD_{50} would require exposure to the contents of 26–83 ml of water from aerial application, 127–414 ml from ground-sprayer application, and 14–45 L from the 25-kl chemigation. Thus, compared with the other methods of application, chemigation would require more than a 500-fold increase in exposure to achieve either a dermal or an oral LD_{50}.

Possible reduction of chemical requirements. Although insufficient research has been conducted to determine whether chemical rates can be reduced with chemigation, considerable benefits have been shown for nutrients such as nitrogen that are highly subject to leaching. When nitrogen is applied at incremental rates by chemigation throughout the growing season rather than in two large amounts early in the season, less is available at any given time for leaching during an intense rainfall. This may reduce the amount of chemical required or, by keeping the nutrient in the rhizosphere longer, may allow the plant to use the chemical more efficiently. There is also substantial evidence that rates of certain herbicides and insecticides may be reduced when applied by chemigation.

Possible reduction of environmental contamination. Although adequate data have not yet been collected to define such reduction, several years of experience with center-pivot systems have shown that, under the same environmental conditions, drift is less with chemigation than with aircraft or ground-sprayer applications.

Economics. A comparison of the cost of chemigation with the cost of aerial or ground application depends on the assumptions made (13,15). Likewise, the cost of applying a particular chemical by chemigation depends on how much water is needed for effectiveness and if the water supply must be supplemented. Table 4 compares the costs of chemigation with the costs of conventional methods of application; both variable and fixed costs of operating the systems are considered. The data indicate that for just one application a year, chemigation is likely to be cost-effective only for chemicals requiring incorporation. With two or more applications a year, however, chemigation is very cost-effective (Table 5). Costs range from 34 to 60% of conventional application costs and decrease significantly as the number of annual applications increases. Because the management advantages offered by chemigation are realized through multiple annual applications, an irrigator is unlikely to use the system only once a year. Chemigation is thus obviously a very economical technique for applying chemicals—normally costing no more than, and usually only one-third to one-half as much as, aircraft or tractor applications.

Effectiveness. Researcher and grower experiences document the effectiveness of fertilizers, herbicides, insecticides, fungicides, nematicides, and growth regulators applied via chemigation. With foliage-applied chemicals such as insecticides and postemergence herbicides, results have been excellent with only 0.5

Table 2. Parathion (ppm) in water with three methods of application

Rate (kg/ha)	Aerial (47 L/ha)	Ground sprayer (234 L/ha)	Chemigation (kl/ha) 6.7	33.5	50.3
1.0	21,000	4,000	149	30	20
0.5	12,000	2,000	76	15	10
0.1	2,000	400	15	3	2
0.05	1,000	200	7	1.5	1

Table 3. Liters of water required for exposure of a 68-kg person to LD_{50} of parathion applied at 0.5 kg/ha by three methods

Exposure[a]	Aerial (47 L/ha)	Ground sprayer (234 L/ha)	Chemigation (L/ha ×1,000) 25	127	190
Dermal, 3,745 mg					
LD_{50} for rats = 55 mg/kg	0.352	1.75	190	951	1,423
Oral, 272–885 mg					
LD_{50} for rats = 4–13 mg/kg	0.026–0.083	0.127–0.414	14–45	69–225	103–336

[a] LD_{50} for rats and human beings assumed to be equal.

Table 4. Costs of a single chemigation and of conventional application of chemicals

Type of chemical	Conventional[a] ($/ha)	Chemigation[b] ($/ha)	Water applied (cm)
Fertilizer	6.20	13.06	1.0
Herbicide	14.00[c]	13.06	1.0
Insecticide	5.60	9.84	0.3
Fungicide	5.60	9.84	0.3
Nematicide	14.00[c]	13.06	1.0

[a] Costs of aerial and ground-sprayer applications assumed to be equal.
[b] Operation cost of 61-ha center pivot (fixed cost of irrigation system charged against irrigation) plus annual fixed cost of chemigation system.
[c] Includes cost of mechanical incorporation.

Table 5. Costs of chemigation and conventional applications of chemicals for representative treatment schedules

Treatment schedule[a]	Chemigation: Fixed cost[b] ($/ha)	Chemigation: Variable cost[c] ($/ha)	Chemigation: Total cost ($/ha)	Conventional total cost[d] ($/ha)	Savings with chemigation ($/ha)
1F	8.56	4.50	13.06	6.20	−6.86
1F,1H	4.28	9.00	13.28	20.20	6.92
2F,1H	2.85	13.50	16.35	26.40	10.05
2F,1H,1I	2.14	14.78	16.92	32.00	15.08
2F,1H,1I,1Fg	1.71	16.06	17.77	37.60	19.83
2F,1H,2I,1Fg	1.43	17.34	18.77	43.20	24.43
2F,1H,4I	1.22	18.62	19.84	48.80	28.96
3F,1H,4I	1.07	23.12	24.19	55.00	30.81
3F,2H,4Fg	0.95	27.62	28.57	69.00	40.43
3F,2H,5I	0.86	28.90	29.76	74.60	44.84

[a] Number of applications per year and type of chemical; F = fertilizer, H = herbicide, I = insecticide, Fg = fungicide.
[b] Assumed $4,000 fixed cost of chemigation system plus $2/ha annual maintenance cost.
[c] Based on operating cost of 61-ha center pivot.
[d] See Table 4 for costs of single applications.

L a.i. per 10–50 kl of water per hectare. The effectiveness of chemigation has been proved over several years of research on a wide variety of both agronomic and horticultural crops.

Requirements and Considerations

Capital outlay. The cost of the chemical injection system components and tanks depends on the type of chemical to be injected but usually ranges from $300 to $5,000. Requirements for the backflow prevention system are state-legislated, but the cost generally ranges from $1,000 to $8,000. On the basis of current requirements, a reasonable estimate of the total capital outlay for a chemigation system is $4,000, the value we used in our analysis of comparative costs. An irrigator can dramatically reduce capital outlay per irrigation and per system by using a mobile chemigation system serving two or more irrigation systems rather than a dedicated chemigation system.

Safety considerations. Assuring the long-term benefits and value of chemigation requires consideration of both human and environmental safety. The backflow of a chemical into a water supply is a recognized potential environmental hazard. Safety considerations for chemigation are well defined, and appropriate practical safety components are commercially available. Certain safety devices are now legislated in some states, and the Environmental Protection Agency is currently considering chemical label requirements that may result in safety devices being essential for legal application of chemicals via chemigation.

Management requirements. Safe and effective chemigation requires very good management. Management requirements are generally well defined and are currently being transmitted to potential users of chemigation by the technology transfer programs of the Cooperative Extension Service.

Outlook

Chemigation is an effective management tool for crop production that is particularly well adapted to center pivots and other continuously moving lateral sprinkler irrigation systems. The advantages greatly outweigh the disadvantages, and costs are generally one-third to one-half those of conventional application techniques.

The use of chemigation has accelerated during the past few years, and an estimated 5.2 million ha were chemigated in the United States during 1985. The rapid development of chemigation technology stimulated scientists to hold national symposia on the subject during 1981, 1982, and 1985 (11,16,18). Information generated by current and developing research programs should lower unit production costs, assure a safe environment, and provide a greater chance for profit by growers. We predict the use of chemigation will continue to increase.

Literature Cited

1. Adams, P. B., and Johnston, S. A. 1983. Factors affecting efficacy of metham applied through sprinkler irrigation for control of Allium white rot. Plant Dis. 67:978-980.
2. Adams, P. B., Johnston, S. A., Kirkun, J., and Carpenter, H. E. 1983. Application of metham sodium by sprinkler irrigation to control lettuce drop caused by *Sclerotinia minor*. Plant Dis. 67:24-26.
3. Ben-Yephet, Y., Siti, E., and Frank, Z. 1983. Control of *Verticillium dahliae* by metam-sodium in loessial soil and effect on potato tuber yields. Plant Dis. 67:1223-1225.
4. Bryan, B. B., and Thomas, E. L., Jr. 1958. Distribution of fertilizer materials applied with sprinkler irrigation system. Univ. Arkansas Agric. Exp. Stn. Res. Bull. 598. 12 pp.
5. Csinos, A. S., Johnson, A. W., and Golden, A. M. 1986. Metalaxyl and fenamiphos applied through irrigation water to control black shank/root-knot complex on tobacco. Plant Dis. 70:210-213.
6. Dowler, C. C. 1984. Applying herbicides postemergence through irrigation. Crops Soils 36:14-16.
7. Dowler, C. C., Rohde, W. A., Fetzer, L. E., Scott, D. E., Jr., Sklany, T. E., and Swann, C. W. 1982. The effect of sprinkler irrigation on herbicide efficacy, distribution, and penetration in some Coastal Plain soils. Univ. Ga. Coll. Agric. Res. Bull. 281. 22 pp.
8. Hubbard, R. K., Asmussen, L. E., and Allison, H. E. 1984. Shallow groundwater quality beneath an intensive multiple-cropping system using center pivot irrigation. J. Environ. Qual. 13:156-161.
9. Johnson, A. W. 1978. Effects of nematicides applied through overhead irrigation on control of root-knot nematodes on tomato transplants. Plant Dis. Rep. 62:48-51.
10. McMaster, G. M., and Douglas, D. R. 1976. Fungicide application through sprinkler irrigation systems. Trans. ASAE 19:1041-1044.
11. Phatak, S. C., Young, J. R., and Chalfant, R. B., eds. 1986. Proc. Nat. Symp. Chemigation 3rd. University of Georgia, Tifton. 170 pp.
12. Santo, G. S., and Qualls, M. 1984. Control of *Meloidogyne* spp. on Russet Burbank potato by applying metham sodium through center pivot irrigation systems. J. Nematol. 16:159-161.
13. Threadgill, E. D. 1985. Chemigation via sprinkler irrigation: Current status and future development. Appl. Eng. Agric. 1:16-23.
14. Threadgill, E. D. 1985. Chemical injection equipment. Proc. Chemigation Saf. Conf. University of Nebraska, Lincoln. 63 pp.
15. Threadgill, E. D. 1985. Introduction to chemigation: History, development and current status. Proc. Chemigation Saf. Conf. University of Nebraska, Lincoln. 63 pp.
16. Young, J. R., ed. 1981. Proc. Nat. Symp. Chemigation. University of Georgia, Tifton. 126 pp.
17. Young, J. R. 1985. Safe chemigation of insecticides. Proc. Chemigation Saf. Conf. University of Nebraska, Lincoln. 63 pp.
18. Young, J. R., and Sumner, D. R., eds. 1982. Proc. Nat. Symp. Chemigation 2nd. University of Georgia, Tifton. 98 pp.